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COMPARATIVE STUDY OF THE ECONOMY ASPECTS OF A DIGITAL ELECTROHYDRAULIC ACTUATOR

C. Brinckmann

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16. Abstract

A digital hydraulic actuator for linear motion, consisting of cylinders in series, is compared with an analog servo actuator with regard to the consumption of pressurized oil as an index of economic operation. A description is given of the economic boundaries in general and of the special case of an actuator in aircraft control.

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1. Symbols

A_P	Piston area $A_P = A_{Pd} = 2A_{Pa}$	cm^2
A_{Pd}	Piston area in digital actuator cylinder	cm^2
A_{Pa}	Piston area in analog actuator cylinder	cm^2
f	Frequency	s^{-1}
D	Displacement expressed in position values	
i	Initial position value for a movement	
j	Final position value for a movement	
K	Consumption factor	
$K_{i,j}$	K for one period between position values i and j	
m_D	Position value for displacement mid-position	
n	Number of pistons in digital actuator cylinders	
Q_a	Analog actuator oil consumption	$cm^3 \cdot s^{-1}$
Q_d	Digital actuator oil consumption	$cm^3 \cdot s^{-1}$
Q_L	Leakage oil consumption	$cm^3 \cdot s^{-1}$
Q_V	Servo valve oil consumption	$cm^3 \cdot s^{-1}$
Tr	Travel	cm
ΔTr	Travel quantization unit	cm
Tr_{max}	Maximum travel	cm
ΔV	Volume quantization unit	cm^3
*	Index for maximum value of K_V	

COMPARATIVE STUDY OF THE ECONOMY ASPECTS OF A DIGITAL ELECTROHYDRAULIC ACTUATOR

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2. Introduction /9*

The digital electrohydraulic actuator which is compared below with a conventional analog servo actuator is essentially a series arrangement of differential positioning cylinders which are accommodated in a common housing (Fig. 1). The distances traveled by the pistons, which are hooked into one another and can be operated in binary fashion with magnetic valves, are stepped in accordance with the principle of binary numbers (binary-weighted) and are limited by stops. Because of their series arrangement, the piston rod executes the sum of movements of the individual pistons [1, 2].

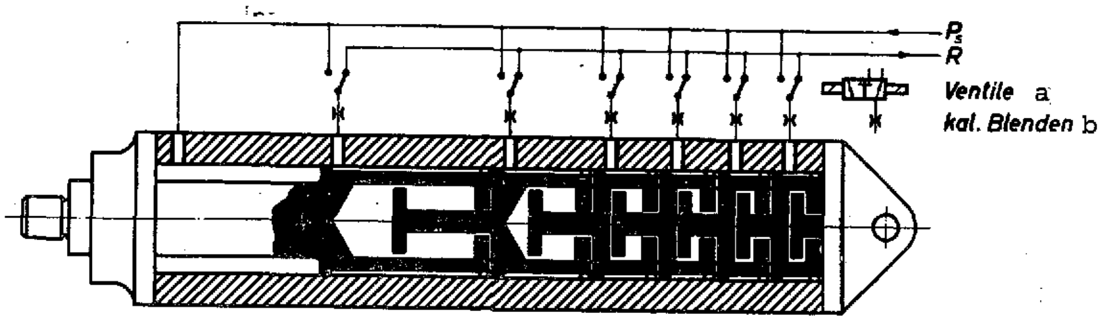

Fig. 1. Digital actuator cylinder with six individual pistons, shown schematically.

Key: a. Valves
b. Orifices

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* Numbers in the margin indicate pagination in the foreign text.

The economy of operation of such an actuator, without consideration of production costs, will be compared here with an analog servo actuator on the basis of pressurized-oil consumption only.

In contrast to the latter, no oil consumption occurs in the digital actuator cylinder when it is at a standstill. On the other hand, consumption in the digital cylinder, at maximum amplitude, can reach a value which is several times that in the analog actuator. This results from the fact that all individual pistons can be involved in producing even the smallest possible output movements.

3. Calculation of Oil Consumption for the Digital Actuator /10

The peculiarity just described will be illustrated with a digital actuator cylinder possessing only n = 3 pistons. Binary weighting means that the travels of the three pistons occur in the ratio of 1 (= 2^0) to 2 (= 2^1) to 4 (= 2^2) (levels of travel). The smallest step width which can occur and thus the quantization unit ΔTr for travel is equal to the travel of the lowest-level piston. Since the greatest overall travel is achieved when pressurized oil is fed into all piston chambers, the addition of individual travels yields maximum travel

$$Tr_{max} = \Delta Tr \cdot \sum_{i=1}^{n} 2^{i-1} = \Delta Tr \cdot (2^n - 1) \quad . \qquad (1)$$

For the quantization unit for travel we can then write

$$\Delta Tr = \frac{Tr_{max}}{2^n - 1} \quad . \qquad (2)$$

By multiplying by piston area A_{Pd} we obtain the quantization unit for the volume to be filled with oil:

$$\Delta V = \Delta Tr \cdot A_{Pd} \ . \qquad (3)$$

The diagram in Fig. 2 indicates, through the coverage of individual fields, the piston chambers, with their levels, which must be filled with pressurized oil in each case to achieve the positions that are possible.

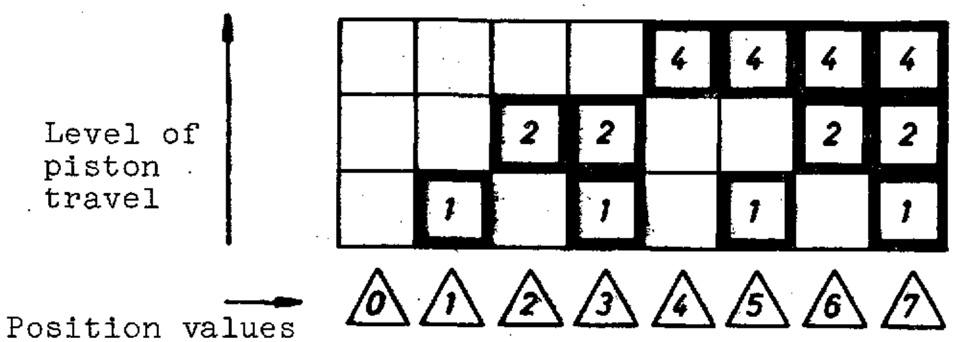

Fig. 2. The combination of levels required to achieve possible positions with n = 3 individual pistons.

The sum of new levels which occur during a position change indicates oil consumption in volume quantization units and will be designated in the following as consumption factor K. As shown in the diagram, oil consumption is 7 units for movements from /11
0 to 7 and back, for instance, and a cycle between position values 3 and 4 likewise requires 7 units.

Since an advance and return movement will be considered in each case, the volume of oil from the differential piston chamber need not be considered, since it is not emptied during return, but is retained for the movement process.

If we study all possible cycles systematically for the magnitude of oil consumption, we can set up the nomographic table in Fig. 3. For position changes of more than one step, it has been assumed that the intermediate positions are adopted individually. The consumption factor for a cycle of movement between any two position values can then be found at the intersection of the corresponding lines.

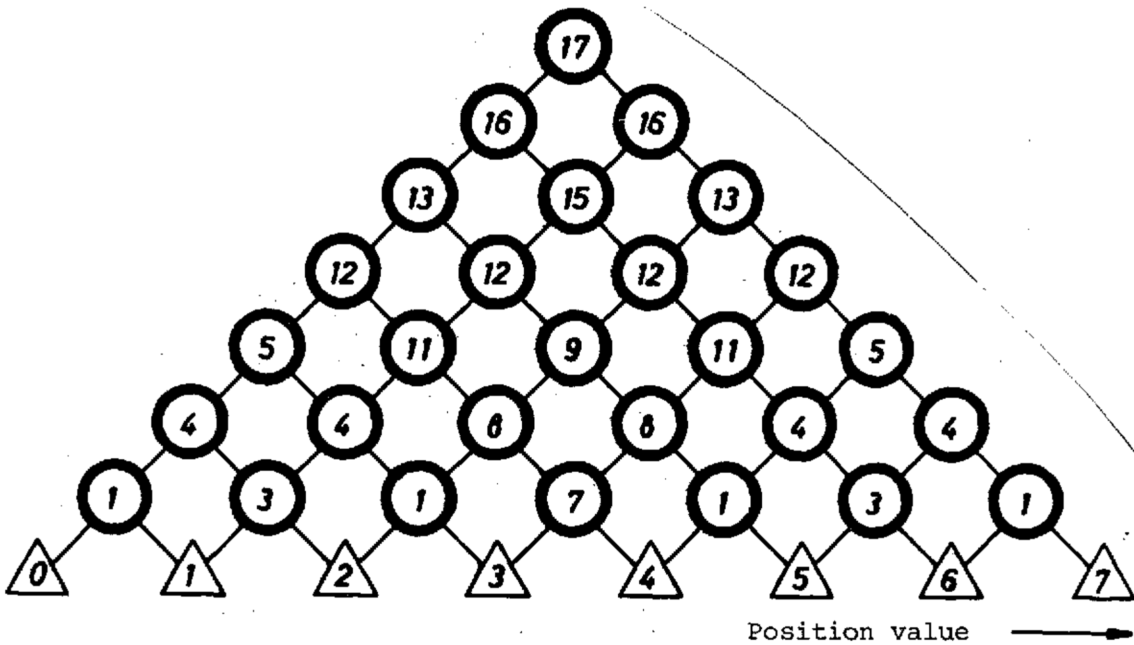

Fig. 3. Consumption factors for a cycle of movement between any position values for n = 3 individual pistons.

It can be seen from this table, for example, that for a travel of just one step, maximum oil consumption of 7 units occurs during movement between position values 3 and 4. For a travel of three steps, maximum oil consumption occurs between position values of 1 and 4 and between 3 and 6, with 11 units each. Using equation (3), we obtain absolute oil consumption as /12

$$Q_d = K \cdot \Delta V \cdot f \quad , \tag{4}$$

where f refers to travel frequency.

A mathematical formulation for the consumption factor can be derived in order to generalize the table in Fig. 3, which is unwieldy for a larger number of pistons. For a digital actuator cylinder with n pistons, consumption factor $K_{i,j}$ for a cycle of movement between position values i and j is

$$K_{i,j} = \sum_{h=i+1}^{j} \left(\sum_{m=0}^{n-1} 2^m \left(\mathrm{INT}(p) - \mathrm{INT}(p - 2^{-m}) \right) \right) \tag{5}$$

where $p = 1 + (|2^{n-1} - h|)/2^m$

for $0 \leq i < j \leq 2^{n-1}$

and INT(e) = integer part of (e).

If displacement D is specified as a difference between position values,

$$D = j - i, \tag{6}$$

the maximum value for the consumption factor falls between position values

$$i^* = 2^q - 1 \tag{7a}$$

and

$$j^* = i^* + H \tag{7b}$$

where $q = \mathrm{INT}\,[\log_2(2^n - D)]$.

Due to symmetry,

$$K_{i,j} = K_{(2^n-1-j),(2^n-1-i)}$$

even the maximum values occur twice in each case. The displacement mid-positions also lie at the middle of possible travel only for a few selected displacements. In general, the displacement mid-position can be found at the position value

$$m_D = \frac{i + j}{2} = i + \frac{D}{2} . \qquad (8a)$$

The displacement mid-positions associated with the occurrence of maximum values for the consumption factor are then at the following position values: /13

$$m^*_{D1} = i^* + \frac{D}{2} \qquad (8b)$$

$$m^*_{D2} = 2^n - 1 - m^*_{D1} . \qquad (8c)$$

At this point it is now possible to calculate all quantities for determining the maximum oil consumption Q_{dmax} of a digital actuator cylinder occurring in the most unfavorable case, using equation (4):

$$Q_{dmax} = K_{i^*, j^*} \cdot \Delta V \cdot f \qquad (9)$$

4. General Comparison with an Analog Servo Actuator

If it is to be possible to make a meaningful comparison with an analog servo actuator, both actuators must be able to produce the same positioning force. In the digital actuator, the force of the front differential piston chamber, with area $A_{Pd}/2$, continually operates against the forces of the individual piston chambers, with area A_{Pd}, so an area of only $A_{Pd}/2$ is effectively available to produce the positioning force. The piston area of an analog actuator cylinder must therefore be

$$A_{Pa} = A_{Pd}/2 \; . \tag{10}$$

The servo valve of an analog servo actuator has a continuous oil leakage consumption Q_L in the hydraulic converter stage, which might, for example, be a nozzle bounce plate system. In most applications, this first stage is followed by a four-way slide valve which controls oil flow to the actuator cylinder. A typical average value might be

$$Q_L = 8 \text{ cm}^3/\text{s}.$$

To this oil consumption, which even occurs at a standstill, can be added the consumption per movement cycle produced by the operating cylinder. Thus for oil consumption of the servo valve only we obtain

$$Q_v = Q_L \tag{11}$$

and for consumption of the overall analog actuator, /14

$$Q_a = Q_L + 2 \cdot A_{Pa} \cdot Tr \cdot f \tag{12}$$

where Tr indicates travel:

$$Tr = \Delta Tr \cdot D \; . \tag{13}$$

The limit of economic operation for a digital actuator cylinder is achieved at that configuration of parameters for which

$$Q_v \leq Q_{dmax} \tag{14a}$$

or

$$Q_a \leq Q_{dmax} \; . \tag{14b}$$

From equation (10) we have

$$2 \cdot A_{Pa} = A_{Pd} = A_P. \tag{15}$$

For comparison with a servo valve only, we then obtain the following from equations (9), (11), and (14a), making use of equations (2) and (3):

$$\left.\begin{aligned}
&Q_L \leq K_{i^*, j^*} \cdot \Delta V \cdot f \\
&Q_L \leq \frac{K_{i^*, j^*} \cdot Tr_{max} \cdot A_P \cdot f}{2^n - 1} \\
&\frac{f \cdot Tr_{max} \cdot A_P}{Q_L} \geq \frac{2^n - 1}{K_{i^*, j^*}}
\end{aligned}\right| \tag{16a}$$

For comparison with a complete actuator consisting of a servo valve and cylinder, we obtain the following from equations (9), (11) and (14b), making use of equations (2), (3), (13) and (15):

$$\left.\begin{aligned}
&Q_L + A_P \cdot Tr \cdot f \leq K_{i^*, j^*} \cdot \Delta V \cdot f \\
&Q_L + D \cdot \frac{f \cdot Tr_{max} \cdot A_P}{2^n - 1} \leq K_{i^*, j^*} \cdot \frac{f \cdot Tr_{max} \cdot A_P}{2^n - 1} \\
&\frac{f \cdot Tr_{max} \cdot A_P}{Q_L} \geq \frac{2^n - 1}{K_{i^*, j^*} - D} \ .
\end{aligned}\right| \tag{16b}$$ /15

The right sides of equations (16a) and (16b) are each functions of displacement and of the number of individual pistons in a digital actuator. According to equations (2) and (13), the following can be used for D:

$$D = (2^n - 1)\cdot\frac{Tr}{Tr_{max}} . \tag{17}$$

Equations (16a) and (16b) are shown graphically in Figs. 4 and 5. The curves, the parameter for which is the number of individual pistons in a digital actuator cylinder, represent the limits below which a digital actuator has a lower oil consumption, even in the most unfavorable operating situation, than a servo valve or a comparable complete analog servo actuator.

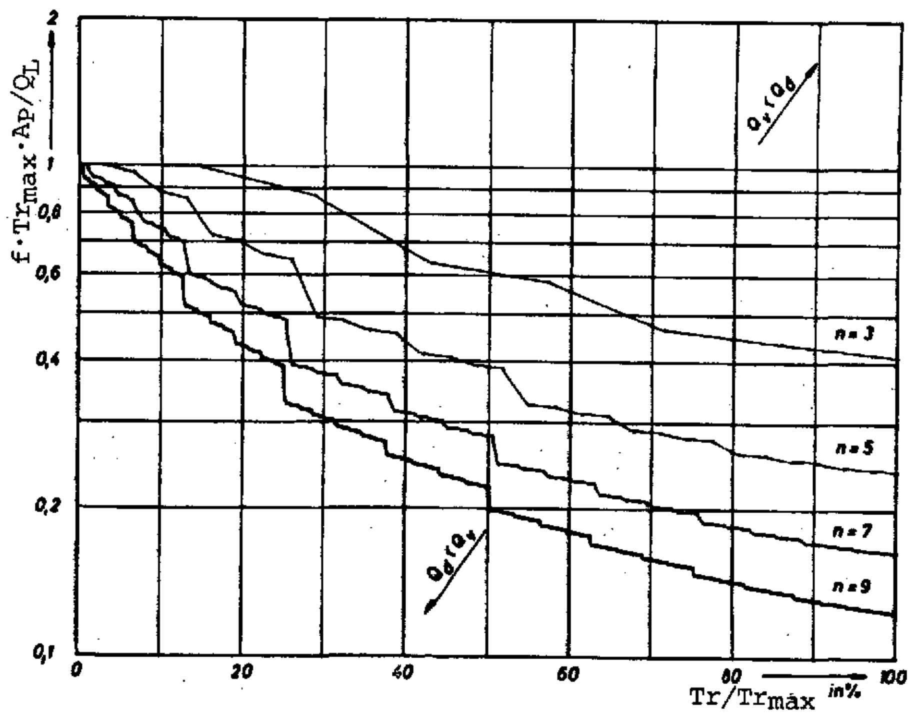

Fig. 4. Boundaries for equal oil consumption in the digital actuator cylinder and analog servo valve.

[Note: Commas in numerals are equivalent to decimal points.]

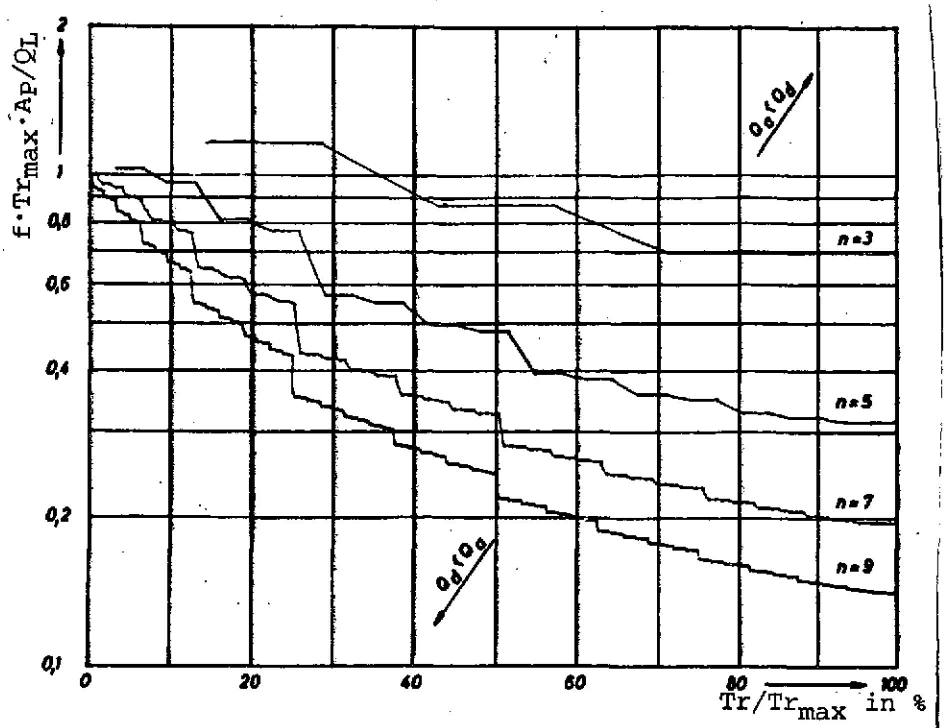

Fig. 5. Boundaries for equal oil consumption in the digital actuator cylinder and analog servo actuator (servo valve with actuator cylinder). /16

5. Evaluation of the Digital Cylinder as an Actuator for Aircraft Control Surfaces

The actuator for control surfaces on an aircraft will be used as an example for a practical comparative evaluation. Let actuation be accomplished in both cases by means of an ordinary analog actuator cylinder which is supplied with pressurized oil with the aid of a four-way slide valve.

In one case, this four-way valve is assumed to be the second amplification stage for the servo valve, and position return is assumed to be accomplished electrically in the control circuit. In the other case, the four-way valve is assumed to be operated mechanically by a digital actuator cylinder operating as the reference element in a sequential control system with mechanical return. In this case, the digital actuator cylinder must have a positioning force at its disposal with which a slide valve is known to be operable even in case of jamming which might occur. We assume /17

$$A_P = A_{Pd} = 2 \cdot A_{Pa} = 1.6 \text{ cm}^2;$$

at a pressure of P_S = 206 bar, common in aircraft hydraulics, positioning force is thus

$$F = A_P \cdot \frac{P_S}{2} = 1650 \text{ N}.$$

Leakage flow is assumed to be

$$Q_L = 8 \text{ cm}^3/\text{s}$$

and maximum travel is assumed to be

$$Tr_{max} = 51.1 \text{ mm}.$$

With these values we then use equation (16a) to make the most unfavorable comparison for the digital actuator, with a servo valve only. The result is shown graphically in Fig. 6 in the form of boundaries, as a function of relative amplitude, for those signal frequencies under which the digital actuator has the lower oil consumption. A parameter for the curves is again the number of individual pistons.

In order to make it possible to evaluate this digital actuator from the viewpoint of oil consumption, we make use of results from flight tests made by the Institut für Flugführung of the DFVLR [3]. /18

It was found here that, regardless of the number of quantization units, the frequency distribution of control horn

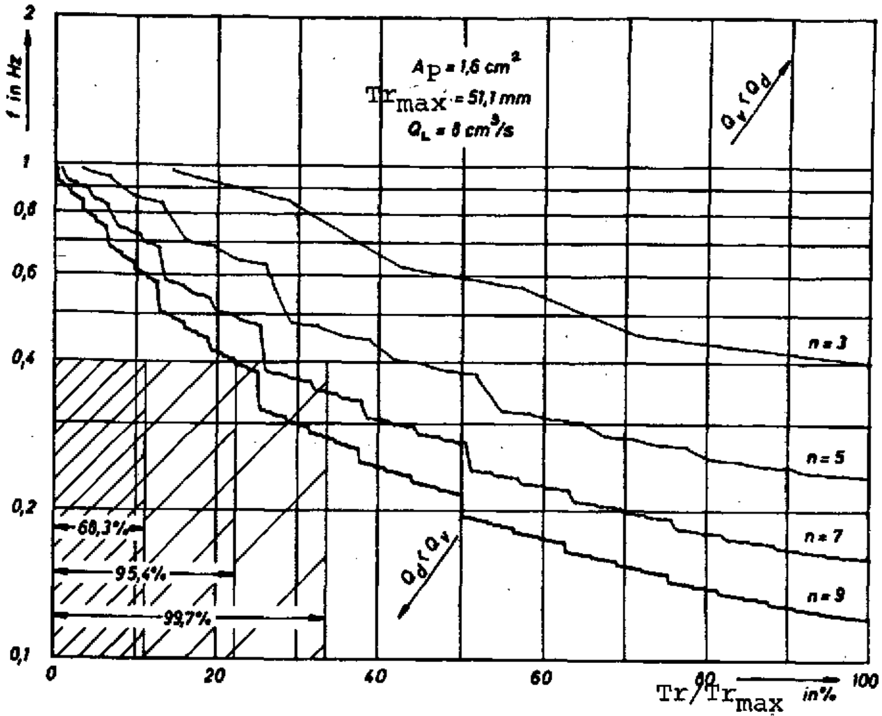

Fig. 6. Boundaries for equal oil consumption in the digital actuator cylinder and analog servo valve; principal operating range in an aircraft control system.

movements for ILS landing approaches flown with the "Pembroke" aircraft configuration corresponds to a normal distribution. The standard deviation of control horn movement was likewise independent of quantization and amounted to 5.6% of maximum deflection. We can conclude from these two facts that 68.3% (95.4%) of the measured control horn movements fell within a range of 11.2% (22.4%) of maximum travel.

It was also found that the performance spectrum for the control horn movements did not extend beyond the range from 0.05 to 0.4 Hz even for the low number of only 15 quantization steps (n = 4).

Aside from special flight situations and under the assumption that the landing approaches in which measurements were taken already represent special performance in flight operation with regard to the demands which they made on the pilot, we can thus conclude that less than 1/4 of piston travel, in a frequency band up to a maximum of 0.4 Hz, can be considered the principal operating range for more than 95% of the control movements.

The principal operating range is indicated as a hatched region in Fig. 6, along with the cumulative frequencies of individual sub-ranges. It can be seen from this graph that even with a resolution of better than 2 $^{o}/oo$ (n = 9 pistons, $2^{n} - 1$ = 511 steps), a digital actuator in an aircraft control system operates more economically in 95% of the positioning movements which occur than a comparable analog servo actuator.

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